Fault Motion

When sufficient deformation occurs in the subsurface with the accompanying buildup of in-situ stresses, a brittle rock will break, creating fractures. In contrast, a ductile rock has plasticity and will deform. Among the various sedimentary rock types, dolomite and limestone are brittle and shale is relatively more ductile (flexible). Brittle rock ~~is~~may be more conducive to inducing seismicity in a disposal environment.

Unconsolidated sediments are also subject to faulting and overpressure. Areas with high sedimentation rates, such as the Gulf of Mexico, develop growth faults in response to active compaction and gravity load on unstable slopes. The movement on the growth fault is triggered by episodic periods of rapid sedimentation. Conversely, decreased pressure through pumping out ground water could also cause slip along the fault. Both causes effectively remove water from the sediment layer and increasing compaction of sediments, and hence increase the density and weight of the material triggering slip along the fault. Growth faults are also examples of shallow faulting unrelated to basement rocks.

~~Earth~~ Reactions to subsurface stress ~~reactions~~ will be accompanied by a level of seismicity that can be recorded with sufficiently sensitive and well placed monitoring devices. The USGS has compiled a map database of all faults in the U.S. believed to have caused earthquakes above magnitude 6 in the last 1.6 million years (USGS, 2004). The seismology community is actively studying the earth's structure, earthquake occurrence, and plate motion; in an effort to not only understand but to also forecast earthquakes. To grasp the difficulty in estimating seismicity potential, it is important to understand the basic aspects of seismicity, and how earthquakes are measured and interpreted.

Basic Seismology

An earthquake (seismic event) occurs ~~when there is~~both at the initial brittle failure ~~along a~~ fault creation, as well as during future episodes of motion (slip) along a fault ~~at depth~~. The ~~resulting brittle failure of the fault results in slip or~~ displacement ~~that~~ motion generates elastic waves that propagate away from the fault. ~~The event can be from a source in, on, or above ground that creates a wave motion in the earth.~~ The movement (propagation) of the seismic wave is governed by laws of refraction and reflection within the geologic layering. ~~Seismic exploration companies create seismic waves to identify structure, layering, and/or exploitable materials such as hydrocarbons in the subsurface.~~ An earthquake (movement within the earth along a fault) gives rise to four types of seismic waves radiating away from the movement source (rupture zone or focus). These movements can be considered in two major wave categories, body waves and surface waves. Body waves travel through the earth, while surface waves are trapped near the surface of the earth. Body waves are faster than surface waves and are thus the first seismic waves to arrive; however, surface waves because they are trapped near the earth's surface decay more slowly with distance and can cause the most damage. As waves travel, their amplitude decays with increasing distance. Each of the four specific wave types has a characteristic motion (compressive, shear, or elliptical), frequency, wavelength, and velocity of propagation, with a corresponding wave equation. Travel velocities range from less than 1 to over 7 kilometers per second in the crust and upper mantle. For a specific location, there can be three to four arrival times of the different waves in quick succession whose difference in arrival time can be used to locate the source of the waves.

Large earthquakes are typically followed by smaller ones as stresses redistribute with the smaller earthquakes producing smaller waves. Crossing wave forms may create constructive or destructive interference. An earthquake series is a set of events related in space and time with similar characteristic wave signatures. In a series of earthquakes, the largest event is the main shock, with the rest classified based on whether they occur before (foreshock) or after (aftershock) the main shock. Detailed analysis of an earthquake series, with sufficiently detailed readings, can be used to map the causative fault location. Observation suggests that aftershocks occur across the fault plane of the main shock as stresses are shifted to new locations. The length of time encompassing the foreshocks and aftershocks is not uniformly defined, but the number of aftershocks decreases significantly over time (Richardson, 2013).

The size of an earthquake can be described with different magnitude scales based on the seismic waves generated: local or Richter (M_L), surface-wave (M_s), body-wave (m_b), or Moment magnitude (M_w). The first three ($M_{L,}$ $M_{s \text{ and}}$ m_b) use formulas combining amplitude from seismometer recordings with a correction based on the distance the wave has traveled correcting for the spatial decay of the waves. Additionally, M_s and m_b incorporate the seismic wave period (peak to peak).

Moment magnitude (M_w or M) is proportional to the release of energy from large earthquakes (Seismic Moment, M_o). M_o is a physical measure of the size of the earthquake that is dependent on the area of the fault, the average displacement on the fault (slip), and shear modulus (rock rigidity). M_w is applicable to all sizes of earthquakes, giving similar results to either $M_{s \text{ or}}$ m_b for smaller earthquakes. In large earthquakes (M>5), the energy released is proportional to the amount of slip along the fault plane (Wells and Coppersmith, 1994; Båth, 1966). In preparation of this report, EPA used magnitude values reported in earthquake catalogs (see Appendix L), for the case study evaluations.

The Modified Mercalli Intensity scale is discussed under the Seismic Risk section since it relates to damage resulting from an earthquake.

Science of Seismic Interpretation

Technology used to record seismic waves has progressed from the original weighted spring or oscillating pendulum seismometers to complex seismographs that track motion in three perpendicular directions over broad frequency bands and record them digitally. In addition to faulting events, seismometers also record ground motions caused by a wide variety of natural and man-made sources, such as the motion of cars and trucks on the highway, building demolition, mining explosions, lake level changes, cavern collapse, sonic booms, hurricanes and ocean waves crashing on the beach. Instrumentation improvements have provided enhanced recording sensitivity. The difference in quality of earthquake data from today's seismometers to those from twenty or thirty years ago should be considered when viewing historic earthquake data. Knowing the details of the seismometer used to acquire the data is beneficial, noting that some older seismometers are still in service. Appendix L discusses the various earthquake databases.

The recordings of earthquakes must be analyzed to determine the origin (latitude, longitude and depth) of the faulting. At least three separate locations of seismograph readings are needed to locate the surface position (epicenter) of the earthquake. A model, with the major earth velocity layers, is used to separate the signals received into the different waves to determine the depth at which the earthquake occurred (hypocenter). Seismic wave velocity is a function of rock porosity, fluid saturation, compaction, and overburden pressure; or in rock mechanics terms, the elastic modulus, permeability, and density. For earthquake modeling, the Earth (surface through mantle) is divided into thick layers with uniform velocities. For exploration seismic modeling, a much more refined velocity model is needed to focus on the target interval.

Seismometers in the permanent monitor grid in most of the continental U.S. are spaced up to 200 miles (300 km) apart. With this spacing, the system is capable of identifying events down to approximately magnitude 3 or 3.5, although in some areas this may extend to 2.5. In tectonically active areas such as the continental western margin and New Madrid Seismic Zone, the seismometer spacing is closer, resulting in more accurate earthquake locations. Additionally, closer grid spacing generally measures events of smaller magnitude.

Beginning in 2007, the IRIS EarthScope Transportable Array has travelled systematically across the continental U.S. The deployment of this array has led to an increase in lower-level seismic event detection that was not previously possible. This array includes seismometers spaced every 70 km, and is capable of picking up events down to around magnitude 1. Subsequent research reports have concluded that the added modern seismometer density provided significant additional information, including improved seismicity rates for hazard analysis, and identification of earthquake swarms and clusters (Lockridge et al., 2012, Frohlich, 2012). Consequently, the number of recorded seismic events over time is partly a function of the seismometer array density and instrument sensitivity.

The accuracy of earthquake focal depth determination is related to the seismometer grid density, seismometer quality, and the detail (quantity and accuracy) of the velocity model used to locate the event. Hypocenter depths are often reported using a default value for the geographic area model. On initial event notifications, default depths will have similar depth uncertainties. For example, a depth of 5 km (16,500 feet) may have a vertical uncertainty between three and five km (10,000 to 16,500 feet). Generally, accurate focal depths (within less than 300 m (1000 feet) vertically) are available only through special investigations, where the waves from the seismometers are individually analyzed with human assessment. The best depth estimates occur when a number of seismic instruments are within kilometers of the surface location of the earthquake.

According to the 2012 USGS glossary, the best located event has an uncertainty at the hypocenter of 100 m (300 feet) horizontally and 300 meters (1,000 feet) vertically. This small area of uncertainty may apply in California, but in the well constrained New Madrid Seismic Zone, Deshon (2013) noted, "Absolute earthquake location is a function of location algorithm, velocity model, event-station geometry and pick quality." Deshon (2013) found hypocenter locations moved up to seven km in depth and three km geographically, by incorporating different phases in the model.

Natural resource exploration firms have used various seismic reflection techniques for years to better image the subsurface in three dimensions. The additional quality gained by increased recording density from a regional two-dimensional (2D) survey to a tightly spaced three or four-dimensional survey is remarkable. Passive seismic recordings are now in use either in active seismic areas or producing hydrocarbon fields with microseismicity to further refine the subsurface structure (Shemeta et al., 2012; Verdon et al., 2010; Martakis et al., 2011).

There are a series of different seismic event reports available from the USGS Earthquake website that fit different needs. Initial seismic event reports, generated within hours of the event, are designed to help with emergency response, and are preliminary with a large location uncertainty. Later reports generally have increased accuracy (magnitude and location), as more information has been incorporated and the standard event modeling has been applied.

SEISMIC RISK

Seismic hazard represents the potential for serious seismic events, whereas risk is the potential damage to people and facilities that may result from the earthquake. Induced seismicity risk evaluates the potential for triggering an earthquake, by altering conditions and initiating movement along a preexisting, optimally oriented fault.

In 1977, Congress passed legislation to reduce the risks to life and property from future earthquakes in the United States through the establishment and maintenance of an effective earthquake hazards reduction program primarily designed to promote safe surface designs. As a result, USGS provides hazard maps used in risk assessments (Appendix M). Hazard typically relates to magnitude whereas risk is associated with intensity. The intensity scale describes how strongly the earthquake was either felt or the degree of damage it caused at a specific location. A strong earthquake yields different levels of intensity based on distance from the epicenter and local surface geology as well as the size of the earthquake. The USGS has instituted a ‘Have you felt it?’ campaign to increase the epicenter location accuracy and to better define the intensity according to the Modified Mercalli Intensity Scale[1]. The Modified Mercalli Intensity Scale is used to map surface effects for a given earthquake with scale increasing with amount of damage.

Surface and near-surface designs of structures are developed by engineers for projects ranging from water reservoirs, deep tunnel construction, or horizontal well drilling. These structures are designed to withstand existing and potential stress, including seismically created stress from strong ground motion (Pratt et al, 1978; Roberts, 1953; Schmitt et al., 2012; Coppersmith et al., 2012).

To understand how risk varies for surface versus subsurface structures, consider first the intensity difference. Seismic shear waves or short-period surface waves ~~are the most likely to be felt~~cause the greatest structural damage through a combination of amplitude and duration of shaking., ~~having the greatest amplitude and a motion similar to ocean waves.~~ For the most damaging earthquakes, the earth’s surface moves very similar to the surface of the ocean in a storm. Consider the difference in motion on a ship at the top of the mast, main deck, and sea anchor. In simplistic terms, this would correspond to the top of a high-rise building, ground level structures, and deep structures such as a wellbore. Accordingly, a wellbore cemented through various layers of rock will undergo little motion.

Serious damage from large earthquakes occurs not from the primary fault motion, but from the secondary processes: landslides, subsidence, liquefaction, and surface fault displacements, combined with failure of engineered structures not designed for strong ground motion. High risk is also present

[1] http://earthquake.usgs.gov/learn/topics/mercalli.php

along coastlines from submarine earthquakes, or on large bodies of water, in the form of large waves or erratic waves crashing on shorelines (tsunami and seiche, respectively).

Most reports cover damage at or above surface ground level. The USGS compiled a summary of earthquakes, over 4.5 magnitude, in the United States between 1568 and 1989 (Stover and Coffman, 1993), describing any damage that was observed including shallow and deep wells. The report covered tens of thousands of earthquakes. Forty-three wells were mentioned predominantly in connection with temporary turbidity or fluid level changes with fewer than ten damage reports. Most of these wells were shallow water wells. Damage was frequently minor, from a tile falling off to a crack in the surface casing. The most applicable report was for the May 2, 1983, earthquake in Fresno County, California: "In the oil fields near Coalinga, surface facilities such as pumping units, storage tanks, pipelines, and support buildings were all damaged to some degree. … Subsurface damage, including collapsed or parted well casing, was observed only on 14 of 1,725 active wells."

UIC programs require that operators run a mechanical integrity test after an injection well workover (repair casing or replace tubing and/or packer). The workover report typically lists the problem repaired, but does not identify the cause of the problem. UIC program directors also have discretionary authority, in cases of earthquakes, to require additional measures such as mechanical integrity testing, as necessary to protect USDWs.